

CONSISTENCY OF AMBIPOLAR DIFFUSION MODELS WITH INFALL IN THE L1544 PROTOSTELLAR CORE

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ABSTRACT

Recent high-resolution studies of the L1544 protostellar core by Tafalla et al. and Williams et al. reveal the structure and the kinematics of the gas. The observations of this prestellar core provide a natural test for theoretical models of core formation and evolution. Based on their results, the above authors claim a discrepancy with the implied infall motions from ambipolar diffusion models. In this paper, we reexamine the earlier ambipolar diffusion models, and conclude that the L1544 core *can* be understood to be a magnetically supercritical core undergoing magnetically diluted collapse. We also present a new ambipolar diffusion model specifically designed to simulate the formation and evolution of the L1544 core. This model, which uses reasonable input parameters, yields mass and radial density distributions, as well as neutral and ion infall speed profiles, that are in very good agreement with physical values deduced by observations. The lifetime of the core is also in good agreement with mean prestellar core lifetimes estimated from statistics of an ensemble of cores. The observational input can act to constrain other currently unobserved quantities such as the degree of ionization, and the background magnetic field strength and orientation near the L1544 core.

Subject headings: diffusion — ISM: clouds — ISM: individual (L1544)
— ISM: kinematics and dynamics — ISM: magnetic fields — MHD —
stars: formation

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1. Introduction

That only a very small fraction of the mass in molecular clouds is ultimately converted into stars is well established by observations (e.g., Zuckerman & Palmer 1974; Carpenter et al. 1993; Fuller 1994). Mouschovias (1976, 1977, 1978) proposed that the observed inefficiency in star formation is naturally explained by molecular clouds being supported against gravitational collapse by interstellar magnetic fields. Collapse in the interior flux tubes of a cloud is initiated by ambipolar diffusion, the gravitationally-induced drift of neutral gas with respect to plasma and magnetic field. Extensive discussion of various aspects of star formation in magnetic clouds, including the role of ambipolar diffusion, can be found in the reviews by Mouschovias (1987), Shu, Adams, & Lizano (1987), McKee et al. (1993), and Mouschovias & Ciolek (1999).

Early axisymmetric calculations considered the initial quasistatic evolution driven by ambipolar diffusion (Mouschovias 1979; Nakano 1979; Lizano & Shu 1989). Fiedler & Mouschovias (1992, 1993) presented detailed numerical simulations showing the formation and subsequent collapse of supercritical cores in two-dimensional, axisymmetric, isothermal, self-gravitating, magnetic model molecular clouds. The flattening of the cloud along the magnetic field lines in these models was used in companion studies by Ciolek & Mouschovias (1993, 1994; hereafter CM93 and CM94, respectively), who modeled the formation of cores by ambipolar diffusion in disk-like magnetic clouds, including the effects of charged and neutral dust grains in their calculation. Disk-like model clouds were also used by Basu & Mouschovias (1994, 1995a, b; hereafter BM94, BM95a, BM95b), who studied the roles of rotation and magnetic braking in the evolution of cores. The effect of an external ultraviolet radiation field, which ionizes the outer regions of a cloud, was incorporated into these models by Ciolek & Mouschovias (1995; hereafter CM95). Qualitatively, the results of these calculations were quite alike: supercritical cores formed due to ambipolar diffusion and went on to collapse dynamically while embedded in magnetically supported (subcritical) clouds. These studies, as well as other magnetic models without ambipolar diffusion (e.g., Tomisaka 1996; Li & Shu 1996; Nakamura et al. 1999), show that collapsing supercritical regions should have an oblate shape.

Past comparison of observed cores with ambipolar diffusion models has yielded positive results. A model for the Barnard 1 cloud was presented by Crutcher et al. (1994); core properties predicted by their model (such as the mass, mean density, and magnetic field strength) were found to be in excellent agreement with observed values (in some instances, differing by less than 10%). In addition, sub-mm continuum observations of prestellar cores (Ward-Thompson et al. 1994; André, Ward-Thompson, & Motte 1996), yield density profiles that are in reasonable agreement with those developed in the ambipolar diffusion

models. Benson, Caselli, & Myers (1998) measured the velocity difference between NH_3^+ and neutral molecules (C_3H_2 and CCS) in sixty dense cores; they noted that their upper limit on the ion-neutral drift speed ($\simeq 0.03 \text{ km s}^{-1}$) is consistent with our published models of core formation and contraction due to ambipolar diffusion.

The L1544 cloud, located in Taurus, seems to be a particularly well-suited candidate for comparison with theoretical models.⁴ Ward-Thompson et al. (1994) suggested that the L1544 core could be a transitional object between a starless core and a core with an IRAS source. As such, the evolutionary state of L1544 could correspond to a recently formed supercritical core which is entering the stage of rapid infall, according to the magnetic models described above. Recent observations by Tafalla et al. (1998, hereafter referred to as T98) indicate that L1544 does show infall on scales of 0.1 pc. More recently, Williams et al. (1999, hereafter referred to as W99) have presented a high-resolution interferometric study of the L1544 core, which allows them to map the kinematics of the ionized species N_2H^+ down to radii ~ 0.02 pc. In both papers, significant infall motions are detected and used to call into question the applicability of the ambipolar diffusion models presented by, e.g., CM95 and BM94. A further point in favor of relatively rapid infall motions is the relative statistics of cores with and without embedded protostars, implying a starless core lifetime of ~ 1 Myr (e.g., Lee & Myers 1999).

In this paper we investigate whether ambipolar diffusion models are relevant in explaining the formation and evolution of the L1544 core. In § 2 we reexamine the results of the earlier ambipolar diffusion models in light of the new observational surveys. We find that, in reality, many of the results of the earlier models are consistent with the infall deduced from observations, if the infall region is taken to represent a portion of the supercritical core. In § 3 we present a new ambipolar diffusion model specifically designed to simulate the evolution of the L1544 core. This particular model uses as input data quantities well within the observationally allowed region of physical parameters. Our results are summarized in § 4.

2. Comparison of Earlier Ambipolar Diffusion Models With Recent Observations

A key result of axisymmetric numerical simulations of magnetically regulated star formation (Fiedler & Mouschovias 1993; CM94, CM95; BM94, BM95a, BM95b) is the formation of an inner region with supercritical mass-to-flux ratio. A supercritical region

⁴This is especially true since surveys by Moneti et al. (1984), Goldsmith & Sernyak (1984), and Heyer et al. (1987) have provided ample indirect evidence to suggest that the large-scale evolution of the Taurus dark clouds is magnetically controlled.

can only form when the central column density (indirectly, the density as well) exceeds a critical value effectively determined by the background magnetic field strength. A supercritical region with size proportional to the thermal critical length scale (see § 3) at the critical column density begins rapid collapse and effectively separates from its subcritical surroundings. Scaling laws for the sizes and masses of such cores are given by BM95b. The cores are characterized by power-law profiles in density, magnetic field components, and angular velocity. The innermost regions have density profiles approaching r^{-2} , but the outer regions (where most of the mass is contained) have progressively shallower slope, so that if we write $\rho_n \propto r^s$, the mass-weighted mean \bar{s} falls between -1.5 and -1.7 for the various models (CM94, CM95; BM94, BM95a, BM95b). The shallowness of the outer profile is due to increasing magnetic support (alternatively, decreasing mass-to-flux ratio) in the outer core. The cores are flattened due to the remaining significant magnetic support, with typical axial ratios in the range $0.25 - 0.33$. An individual observed core is best compared with theory while keeping the whole ensemble of models in mind (e.g., see the parameter study done by BM95a, BM95b), rather than comparing with a single standard model. This is due to the considerable observational uncertainty in input parameters such as the background magnetic field strength and ionization fraction, as well as real variations allowed by nature. Below, we interpret the L1544 observations in terms of an overall understanding gained from the parameter studies.

A point of general agreement of the models with observations is the conclusion of T98 that the overall density profile in L1544 is shallower than r^{-2} . They find an approximate fit with an $r^{-1.5}$ profile over a scale of 0.1 pc. Several simplifying assumptions are used to obtain this estimate (see T98), and error bounds are not explicitly estimated, although r^{-1} and r^{-2} profiles are ruled out. We point out that an approximate $r^{-1.5}$ density profile in a prestellar core is inconsistent with a scale-free isothermal ball of gas, but *is* in reasonable agreement with the magnetic models discussed above. An apparent disagreement with the magnetic models as stated by T98 and W99 is the evidence for extensive inward motions, of order 0.1 km s^{-1} , from scales of 0.1 pc (T98) down to 0.02 pc (W99). The claim that these motions exceed that of the magnetic models over similar ranges in length and density is based on a comparison with the standard models of the above studies.

We first compare the W99 results with the existing models, since infall motions on the small scales ~ 0.02 pc are more easily produced in these models. The essence of W99’s claim is that at radius ≈ 0.02 pc, where the inferred density is $\approx 4 \times 10^5 \text{ cm}^{-3}$, the inferred infall motions for the ionic species N_2H^+ , $\approx 0.08 \text{ km s}^{-1}$, greatly exceed those of ambipolar diffusion models. We refer the reader to W99 for an exposition of the significant uncertainties in obtaining these numbers. For the remainder of this paper, we take these numbers at face value. When we examine the standard model 2 of BM94 and the standard

B_{UV} model of CM95 (scaling the results to the estimated kinetic temperature 12 K), we find that the infall is indeed slower than these numbers when the *central* density is close to $3 \times 10^5 \text{ cm}^{-3}$, i.e., BM94’s model 2 has ionic infall velocity $v_{i,r} = -0.012 \text{ km s}^{-1}$ and CM95 has $v_{i,r} = -0.010 \text{ km s}^{-1}$. However, the observations, which have spatial resolution $\approx 0.01 \text{ pc}$, cannot determine the central density. Therefore, it is prudent to compare the evolutionary models at all possible times when the density at radius $\approx 0.02 \text{ pc}$ is in approximate agreement with the estimated density $\approx 4 \times 10^5 \text{ cm}^{-3}$. It is striking that the development of a power-law density profile in the magnetic models yields an asymptotic value of the density at this radius that is very close to the observed one. At later times, when supercritical collapse is well developed, the density at $r = 0.02 \text{ pc}$ is $9 \times 10^5 \text{ cm}^{-3}$ and $6 \times 10^5 \text{ cm}^{-3}$ in the BM94 and CM95 models, respectively⁵. At the same radius, the asymptotic values of $v_{i,r}$ are -0.11 km s^{-1} and -0.07 km s^{-1} in the same two models. Since the likely inclination angle θ for the disk is $15^\circ - 30^\circ$ (see § 3), the $\cos \theta$ factor due to the inclination of the disk can reduce the maximum line of sight velocity by a factor of only $0.87 - 0.96$. Hence, we conclude that the infall observations of W99 are *not* in disagreement with the standard magnetic collapse models if the cores are in a later stage of development, with an unresolved central density $\gg 10^5 \text{ cm}^{-3}$. Such models are typically characterized by background magnetic field strengths of $B_{\text{ref}} \approx 30 \mu\text{G}$ and ionization fraction $x_i \approx 10^{-7}$ at a neutral density $\approx 10^4 \text{ cm}^{-3}$. Indeed, W99 themselves comment that their results may be in agreement with the rapid infall observed in the model of Li (1998) if late time collapse is considered. We are in agreement with this statement since the model of Li (1998), while restricted to an unnatural spherical geometry in the presence of magnetic fields, and lacking the quantitatively important magnetic tension force⁶, reproduces qualitatively the broad features of infall found in the more detailed models described above.

The evidence for a later stage of evolution is strengthened by the millimeter dust continuum measurements of Ward-Thompson, Motte, & André (1999), whose high-resolution observations establish a flattening of the column density profile of L1544 on inner scales of $\sim 10^3 \text{ AU}$, with a central column density $N \approx 10^{23} \text{ cm}^{-2}$. This central column density places the evolutionary state of the core between the times t_3 and t_4 in most of our models (see § 3), corresponding to a central density in the range $3 \times 10^6 - 3 \times 10^7 \text{ cm}^{-3}$.

On larger scales of $\sim 0.1 \text{ pc}$, T98 detect infall motions with maximum values $\approx 0.1 \text{ km s}^{-1}$. These motions *are* somewhat greater than the infall speeds presented in the standard

⁵Another interesting property of these distributions (and power-laws in general) is that the mean value within any radius is of the same order as the value at that radius; typically just a few times greater.

⁶Due to its nature, such a model cannot predict the magnetic field geometry or the aspect ratio of the core.

models mentioned above. At a radius $r = 0.1$ pc, the standard model 2 of BM94 and the B_{UV} model of CM95 yield neutral infall speeds of -0.06 km s $^{-1}$ and -0.04 km s $^{-1}$, respectively (again, for $T = 12$ K). The parameter study of BM95a and BM95b reveals two general means by which this factor ~ 2 (or slightly higher due to disk inclination) discrepancy can be resolved: (1) A lower background magnetic field strength, yielding a lower critical density for collapse and consequently a larger supercritical core (see BM95b, models 5 and 6). (2) A lower ionization fraction, yielding relatively more rapid infall at all times (see BM95a, models 8 and 9). Both magnetic field strengths and ionization fractions are characterized by appreciable observational uncertainty. In this paper, we concentrate primarily on the first possibility; a lower background magnetic field strength. Model 6 of BM95b can be interpreted as having a B_{ref} of about $10\mu\text{G}$. The central flux tube initially has a critical mass-to-flux ratio, although the rest of the cloud is initially subcritical. Results of this model, presented in BM95b (see their Fig. 6) shows an extended infall zone due to the low density at which a supercritical core is formed. Using $T = 12$ K yields neutral and ionic infall velocities $v_{n,r} = -0.11$ km s $^{-1}$ and $v_{i,r} = -0.09$ km s $^{-1}$ at $r = 0.1$ pc. Significant infall is actually present at even larger radii in this model.

Our point in reviewing these models is not that any single one fits the observations of L1544 exactly, but that the observed features are broadly consistent with features found in one or many previously published models which use reasonable input parameters. Therefore, the L1544 core can very likely be modeled as a supercritical core undergoing magnetically diluted collapse. In the following section, we present a new model which can simultaneously match as many features of the L1544 core as possible.

3. An Ambipolar Diffusion Model For L1544

We now turn to a model designed to more accurately simulate inferred quantities for the L1544 core. Dimensionless parameters used as initial input for this model are: a central mass-to-flux ratio (in units of the critical value for collapse) $\mu_{c0} = 0.80$, and a reference state column density lengthscale $l_{\text{ref}} = 7.5\pi$. (The definition and meaning of these and the other free parameters specifying our disk models are discussed in CM93, CM94, CM95, and BM94, BM95a, b.) Since there have been no significant azimuthal velocities detected in L1544, we neglect for now the effect of rotation and magnetic braking. We do account for the effect of an external ultraviolet radiation field acting on the cloud; the dimensionless parameters $\zeta_{\alpha_0,UV,CR}$ ($\equiv \zeta_{\alpha_0,UV}/\zeta_{CR}$, where $\zeta_{\alpha_0,UV}$ is the UV ionization rate of neutral atomic species α_0 and ζ_{CR} is the cosmic-ray ionization rate), which fix the UV ionization rates at the cloud boundary, are the same as those listed for models A_{UV} and B_{UV} in Table 1 of CM95, except that they are to be multiplied by a factor $= (5/1.3) = 3.8$, reflecting our use of a cosmic-ray ionization rate $\zeta_{CR} = 1.3 \times 10^{-17}$ s $^{-1}$ instead of the

$\zeta_{\text{CR}} = 5 \times 10^{-17} \text{ s}^{-1}$ used by CM95. As in our previous models, the dimensionless cloud radius ξ_R is taken to be $\gg l_{\text{ref}}$. We select a value of ξ_R such that a mass $\simeq 30 M_{\odot}$ is contained within the dimensional radius $r \simeq 0.45 \text{ pc}$, as estimated for the L1544 cloud by T98 (see their Fig. 1). The mass contained at radii $\gtrsim 0.5 \text{ pc}$, which is required in our models solely for computational purposes — the gravitational field diverges if we abruptly cut off the mass distribution at this radius (see the associated discussion on this point in § 4.1 of Crutcher et al. 1994) — has little effect on the dynamics of the core in our model cloud, and remains essentially fixed in space because of effective magnetic support at large radii (see Figs. 1a-1c). Finally, the collisional effects of grains have been made negligible by assuming relatively large grains, with radius $a = 10^{-5} \text{ cm}$. The larger cross-section of these grains is more than offset by their low abundance relative to the ions (CM93, Ciolek & Mouschovias 1996, 1998). The grains, however, still play a crucial role in the evolution of our model, in that recombination of ions and electrons takes place on their surfaces, which affects the chemical reaction rates and the calculation of the abundances of charged particles throughout the cloud (CM94, Ciolek & Mouschovias 1998).

Physically, the parameters cited above could represent an isothermal cloud with temperature $T = 12 \text{ K}$, initial central density and magnetic field strength (in the equatorial plane of the cloud) $n_{\text{n},\text{c}0} = 4.37 \times 10^3 \text{ cm}^{-3}$ and $B_{\text{z},\text{c}0} = 16.5 \mu\text{G}$, respectively. Because the cloud is only 20% subcritical, $B_{\text{z},\text{c}0}$ is a factor 1.35 greater than the reference value $B_{\text{ref}} = 12.2 \mu\text{G}$, which is the field strength in the outer portion of the cloud. The initial central degree of ionization $x_{\text{i},\text{c}0} \equiv (n_{\text{i}}/n_{\text{n}})_{\text{c}0} = 8.5 \times 10^{-8}$ (where n_{i} is the ion density).

Qualitatively, the overall ambipolar-diffusion-initiated infall that occurs in this model is similar to that which occurred in our previous numerical simulations, cited in the preceding sections. The evolution of the density profile in the model cloud is displayed in Figure 1a at eleven different times t_j ($j = 0, 1, 2, \dots, 10$), when the central density $n_{\text{n},\text{c}}(t_j) = 10^j n_{\text{n},\text{c}0}$; these times are, respectively, 0, 2.27, 2.60, 2.66, 2.680, 2.684, 2.685, 2.6856, 2.68574, 2.68577, and 2.68578 Myr. The central mass-to-flux ratio is equal to the critical value for collapse at a central density $n_{\text{n},\text{c},\text{crit}} = 9.17 \times 10^3 \text{ cm}^{-3}$ for this model, and is achieved at a time $t_{\text{crit}} = 1.30 \text{ Myr}$. As in our earlier studies, an asterisk on a curve indicates the instantaneous position of the critical magnetic flux tube $R_{\text{crit}}(t_j)$ (= radius of the supercritical core). For $r < R_{\text{crit}}$, the mass-to-flux ratio in each flux tube exceeds the critical value for collapse, $(M/\Phi_{\text{B}})_{\text{crit}} = 1/(4\pi^2 G)^{1/2}$. An open circle on a curve locates the central thermal critical lengthscale, $\lambda_{\text{T},\text{c}}(t_j) = C^2/2G\sigma_{\text{n},\text{c}}$, where C is the isothermal speed of sound [= $0.19(T/10 \text{ K})^{1/2} \text{ km s}^{-1}$], G is the gravitational constant, and $\sigma_{\text{n},\text{c}}$ is the central column density. The radius of the core that formed in this model is equal to 0.30 pc. The mass contained in the core is $19 M_{\odot}$; the mean core density is $\langle n_{\text{n}} \rangle_{\text{core}} = 8.0 \times 10^3 \text{ cm}^{-3}$, which is lower than the density for collisional excitation of ammonia (= $1.1 \times 10^4 \text{ cm}^{-3}$). Note

that the core radius is greater than the scale of the observations made by both W99 (= 0.02 pc) and T98 ($\simeq 0.14$ pc), hence, as discussed in § 2, we identify the region studied in these dedicated studies as existing *within* the supercritical core. The logarithmic derivative of the density $s \equiv \partial \ln n_n / \partial \ln r$ is presented in Figure 1b, at the same eleven times t_j . Not long after the formation of the core ($t_j > t_3$), for scales $r \gtrsim 0.02$ pc, s is typically > -1.8 . Figure 1c displays the vertical column density $\sigma_n(r) [= 2\rho_n(r)Z(r)]$ in our models, where $\rho_n(r)$ and $Z(r)$ are the local mass density and disk half-thickness, respectively].

The infall speeds of the neutrals ($v_{n,r}$, *solid* curves) and the ions ($v_{i,r}$, *dashed* curves) are displayed as functions of r for times t_1 through t_{10} in Figure 2. (For L1544, the isothermal sound speed $C = 0.21$ km s $^{-1}$.) In the outer regions of the core, the infall reaches ‘asymptotic’ values for $t_j \gtrsim t_3$. We also note that, for times $t_j \gtrsim t_6$ the relative drift speed between the ions and the neutrals becomes greater in the innermost flux tubes, reflecting effective ambipolar diffusion (due to depletion of ions onto grains; see CM93 and CM94 for a discussion) even during the later stages of the dynamical collapse of the core. This results in a continued redistribution of the mass and magnetic flux in the central flux tubes. M/Φ_B increases significantly in the inner core for $t_j \gtrsim t_6$ (the behavior is similar to that exhibited in Fig. 1c of Ciolek & Königl 1998), and the mass-to-flux ratio throughout the core is not well-approximated as being constant at these later times. Further discussion on the role of ambipolar diffusion during the later stages of core collapse, such as when a core approaches the formation of a central point mass (i.e., a protostar) and its subsequent evolution can be found in Basu (1997) and Ciolek & Königl (1998).

We now apply our results to the L1544 core. Assume that the symmetry axis of our disk-cloud is inclined at an angle θ with respect to the plane of the sky. A schematic diagram of the assumed geometry is presented in Figure 3. For an axisymmetric disk with radius r and half-thickness Z , the projected axial ratio (apparent minor axis/apparent major axis) seen by an observer is

$$q = \sin \theta + \frac{Z}{r} \cos \theta. \quad (1)$$

(Note that, for $\theta = 90^\circ$, $q = 1$, i.e., a disk viewed face-on, while, for $\theta = 0^\circ$, $q = Z/r$, i.e., the disk is seen edge-on.) Maps of the gas and dust distribution in L1544 (e.g., T98, W99; Ward-Thompson et al. 1999) find q in the range 0.46 to 0.6. We adopt a value of 0.53. From the numerical simulation we find that, for the region of the core in the range $0.02 \text{ pc} \lesssim r \lesssim 0.1 \text{ pc}$, $Z(r)/r$ ranges from 0.24 to 0.3. For specificity, we use $Z(r)/r \simeq 0.27$. From this value equation (1) implies a tilt angle $\theta \simeq 16^\circ$ (or, equivalently, the cloud is inclined with respect to the line of sight by an angle $\Psi = 90^\circ - \theta = 74^\circ$). From this geometry it follows that the observed maximum line-of-sight infall will be reduced by the factor $\cos 16^\circ = 0.96$.

In Table 1 we list some of our model predictions for several physical quantities at two different radii in the L1544 core, as well as the recent values measured at the same positions by T98 and W99. The values we list for our numerical results are taken from the curves labeled t_3 in Figures 1a-1c; most quantities change very little for $t_j > t_3$. The only notable change at later times is in $|v_{n,r}|$ and $|v_{i,r}|$ at $r = 0.02$ pc; they increase there by 32% and 26% respectively. As mentioned in § 2, the maximum resolution of the W99 core survey (~ 0.01 pc), although greater than in previous surveys, would still be unable to resolve the inner central density peak in our model, since, for $t_j \simeq t_3$, the radius of this central region is 5.6×10^{-3} pc (see Fig. 1a). Our choice of the data at time t_3 as possibly representing the current evolutionary state of L1544 seems to be reasonably consistent with recent sub-mm observational maps, which resolve nearly uniform column densities on scales $\sim 10^3$ AU. The line-of-sight number column density in the inner (‘flat’) region of our model’s core at $r = 1.2 \times 10^3$ AU is $N_{\text{los}} = (\sigma_n / \sin 16^\circ)(1/m_n) = 2.6 \times 10^{23} (\sigma_n / \sin 16^\circ)(2.33 \text{ a.m.u.}/m_n) = 1.3 \times 10^{23} \text{ cm}^{-2}$; for comparison, André et al. (1999, see their Fig. 2) measure $N_{\text{los}} \approx 10^{23} \text{ cm}^{-2}$ in L1544 at this radial distance. Moreover, Ward-Thompson et al. (1999, see their Table 2) find the density in L1544 on these scales to be $\approx 10^6 \text{ cm}^{-3}$; by contrast, at time t_3 our model has $n_n = 2.2 \times 10^6 \text{ cm}^{-3}$ at this position.

In Table 1 we have also included $|v_{i,r}|$ at 0.14 pc, and $|v_{n,r}|$ at 0.02 pc, neither of which have yet been reported. We note that the ion-neutral drift speed, $v_D \equiv v_{i,r} - v_{n,r} = 0.03 \text{ km s}^{-1}$ at 0.02 pc and 0.04 km s^{-1} at 0.14 pc, is in agreement with our earlier models (see § 2), as well as the observed upper limit of drift speeds in dense cores ($\approx 0.03 \text{ km s}^{-1}$), as deduced by Benson et al. (1998). Examination of Table 1 shows the model results to be in excellent agreement with those values observed in L1544.

The appearance of a circularly symmetric function when tilted by our predicted $\theta \simeq 16^\circ$ is shown in Figure 4 at time t_3 . The contours can represent lines of constant density or column density (similar contours of a model fit to the observed column density are presented in Fig. 2b of W99), or even constant values of the infall speed $|v|$ at any given vertical (z) layer of the cloud. If the cloud is infinitesimally thin, the observed line of sight velocity at any position has magnitude $|v_{\text{los}}| = |v| \cos \theta \sin \varphi$, where $\varphi = \arctan(|z'/x'|)$, and x' and z' are sky coordinates as depicted in Figures 3 and 4. This yields $|v_{\text{los}}| = 0$ along the major axis of the cloud. However, in actuality our model cloud has a finite thickness Z , hence any line of sight through the tilted cloud will pick up some v_{los} if the observed spectral line is optically thin or has its optical depth unity surface within the cloud. A calculation of the predicted spectra in this geometry for various tracers and/or viewing angles is more involved, and will be discussed at a later time.

Our model also makes predictions about other physical quantities in L1544. Figure 5 shows the radial profile of the magnetic field strength in the equatorial plane of the cloud, B_z at the same eleven times t_j as in Figure 1a. At the time of core formation, the central magnetic field strength $B_{z,c,crit} = 19.4 \mu\text{G}$. For $t_j \gtrsim t_3$, B_z is equal to $71 \mu\text{G}$ at $r = 0.02 \text{ pc}$, and $21 \mu\text{G}$ at 0.14 pc . The line-of-sight magnetic field strengths are reduced by the factor $\sin 16^\circ = 0.28$, hence Zeeman measurements would measure a field strength $= 5.79 \mu\text{G}$ at 0.14 pc , and $19.6 \mu\text{G}$ at 0.02 pc . By simultaneously and self-consistently solving the rate equations for the abundances of charged species, (see CM93 and CM95 for discussions), we calculate the total degree of ionization x_i ($=$ atomic ion + molecular ion abundances) as a function of position in the cloud; in this model, $x_i = 1.1 \times 10^{-8}$ at 0.02 pc , and $x_i = 5.6 \times 10^{-8}$ at 0.14 pc .

Finally, our calculation allows us to infer the lifetime of the L1544 core. The evolutionary timescale t_{evol} for this model (i.e., the time taken to go from t_0 to t_{10} , essentially the time to form a central protostar) is $\simeq 2.7 \text{ Myr}$. Since the central mass-to-flux ratio becomes critical at a time $t_{\text{crit}} = 1.3 \text{ Myr}$, the actual amount of time that our L1544 model exists as a *supercritical* core is $\tau_{\text{life}} = t_{\text{evol}} - t_{\text{crit}} = 1.4 \text{ Myr}$. The *detectable* lifetime for ammonia observations is $\tau_{\text{det}} = t_{\text{evol}} - t_{\text{NH}_3}$, where t_{NH_3} is the time (corresponding to $n_{n,c} \geq 1.1 \times 10^4 \text{ cm}^{-3}$) at which ammonia becomes collisionally excited in the core. For our model, $t_{\text{NH}_3} = 1.5 \text{ Myr}$, yielding $\tau_{\text{det}} = 1.2 \text{ Myr}$ ($\approx \tau_{\text{life}}$). This is compatible with the $\sim 1 \text{ Myr}$ lifetime of starless cores advocated in the recent study of Lee & Myers (1999).

4. Summary

Recent studies have presented detailed, high-resolution observations of the L1544 core. These observations play an important role in constraining and testing theoretical models of star formation in molecular clouds. In light of these new observations, we have reexamined previously published ambipolar diffusion models of the formation and collapse of supercritical cores in magnetically supported molecular clouds. We find that, despite the questions raised in the papers associated with these surveys, the general characteristics of supercritical cores in the earlier ambipolar diffusion models are consistent with physical features exhibited in the L1544 core. We have also presented a new numerical simulation designed to more accurately reproduce observed features of L1544, as well as make predictions for heretofore unobserved quantities. The model uses reasonable input parameters well within the physically allowed range. Comparing our results to those measurements obtained in the recent studies, we find the resulting mass and velocity distribution of our theoretical model to be in excellent agreement with values deduced at two distinct radial distances, 0.02 pc and 0.1 pc (e.g., see Table 1). There is also agreement with the mass and column densities deduced by sub-mm measurements of dust emission

on smaller scales. This model allows us to deduce the orientation of L1544 with respect to the plane of the sky ($\theta \approx 20^\circ$), and makes predictions about the line-of-sight magnetic field strength ($B \sin 20^\circ \approx 20 \mu\text{G}$) and degree of ionization ($x_i > 10^{-8}$) at different points in the core. The detectable lifetime of the collapsing core in our L1544 model ($\simeq 1.2 \text{ Myr}$) is comparable to that inferred from statistics of an ensemble of cores (Lee & Myers 1999).

While our model supercritical core is to be compared with the infall zone of the L1544 core, of radial extent $\sim 0.1 \text{ pc}$, our cloud model also yields numbers for the subcritical envelope. However, we have not presented these as predictions for the envelope structure. As discussed in our earlier papers, the outer density structure is strongly dependent on adopted initial conditions. For example, a sharp break in the density profile, with power-law index s dropping significantly lower than -2 just outside the supercritical core, is a feature of models with highly subcritical envelopes (e.g., model 7 of BM95b, and model B_{UV} of CM95). Further modeling of the envelope structure can be guided by new data for the outer regions (e.g., see preliminary data in André et al. 1999).

Hopefully, our new study will stimulate greater interaction between observation and theory, in which observations can more tightly constrain input parameters for theoretical models, and the models can make new predictions for unobserved quantities. Although the occurrence of processes not included in our model cannot be ruled out, our results suggest that current observations of infall in starless cores are compatible with the evolution of cores with supercritical mass-to-flux ratio that have formed through ambipolar diffusion.

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Captions to Figures

Fig. 1.— Spatial profiles of physical quantities, as functions of radius r at eleven different times t_j ($j = 0, 1, 2, \dots, 10$), chosen such that the central density at time t_j is a factor 10^j greater than the initial central density. These times are, respectively, 0, 2.27, 2.60, 2.66, 2.680, 2.684, 2.685, 2.6856, 2.68574, 2.68577, and 2.68578 Myr. An asterisk on a curve, present only after the formation of a supercritical core ($t > t_0$), locates the instantaneous radius of the critical magnetic flux tube. An open circle on a curve marks the instantaneous position of the central thermal critical (\simeq Jeans) lengthscale. (a) Density. (b) The exponent $s \equiv \partial \ln n_n / \partial \ln r$. (c) Vertical column density.

Fig. 2.— Radial component of neutral velocity ($v_{n,r}$, *solid* curves) and ion velocity ($v_{i,r}$, *dashed* curves). Note that the isothermal sound speed C for this model is 0.21 km s^{-1} . The times t_j and the labels on the curves are the same as in Figs. 1a-1c.

Fig. 3.— Schematic diagram showing the assumed geometry and orientation of a disklike model cloud, with radius R and half-thickness Z . The disk symmetry axis, which is aligned with the z -axis, is slanted at an angle θ with respect to the z' -axis, which is taken to lie in the plane of the sky.

Fig. 4.— Appearance of physical quantities in the L1544 core at time t_3 , projected onto axes in the plane of the sky. The curves depict the location of loci of constant physical quantities, such as column density, density, and infall speed (directed toward the origin), for our assumed inclined model cloud. For the column density, the contours represent, respectively (starting from the outermost contour), $2.6 \times 10^{21} \text{ cm}^{-2}$, $3.6 \times 10^{21} \text{ cm}^{-2}$, $4.8 \times 10^{21} \text{ cm}^{-2}$, $6.7 \times 10^{21} \text{ cm}^{-2}$, and $1.2 \times 10^{22} \text{ cm}^{-2}$. For the density, the contours correspond to (in the same order) $1.2 \times 10^4 \text{ cm}^{-3}$, $2.3 \times 10^4 \text{ cm}^{-3}$, $4.0 \times 10^4 \text{ cm}^{-3}$, $8.1 \times 10^4 \text{ cm}^{-3}$, and $2.7 \times 10^5 \text{ cm}^{-3}$; for the infall speed they would represent contours with -0.10 km s^{-1} , -0.12 km s^{-1} , -0.127 km s^{-1} , -0.136 km s^{-1} , and -0.140 km s^{-1} . Similar contours are presented for a model fit column density in Fig. 2b of W99.

Fig. 5.— Profile of the vertical component of the magnetic field in the equatorial plane of the cloud. All times and labels are the same as in the preceding figures.

TABLE 1
PHYSICAL QUANTITIES IN THE L1544 CORE

	Predicted ^a	Observed
$r \simeq 0.14$ pc : ^b		
M	$7.7 M_{\odot}$	$8 M_{\odot}$
$ v_{n,r} $	0.11 km s^{-1}	0.1 km s^{-1}
$ v_{i,r} $	0.07 km s^{-1}	—
$s = \frac{\partial \ln n_n}{\partial \ln r}$	-1.7	~ -1.5
B_{los}	$5.8 \mu\text{G}$	—
$r \simeq 0.02$ pc : ^c		
M	$0.90 M_{\odot}$	$1.2 M_{\odot}$
$ v_{n,r} $	0.14 km s^{-1}	—
$ v_{i,r} $	0.11 km s^{-1}	0.08 km s^{-1}
n_n	$3.3 \times 10^5 \text{ cm}^{-3}$	$4 \times 10^5 \text{ cm}^{-3}$
B_{los}	$19.6 \mu\text{G}$	—

^a Assuming a disk tilt-angle $\theta = 16^\circ$.

^b Observed values taken from T98.

^c Observed values taken from W99.

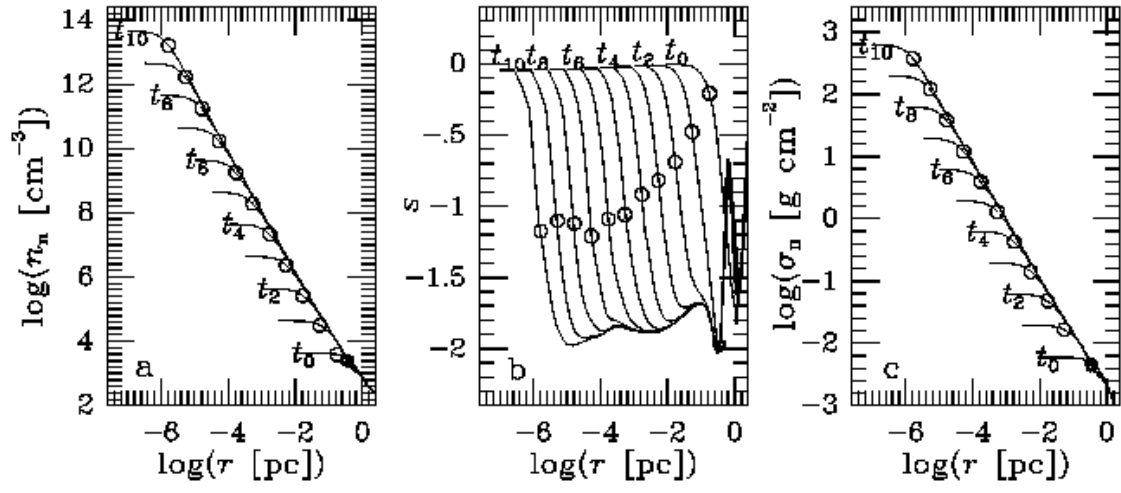


Fig. 1.—

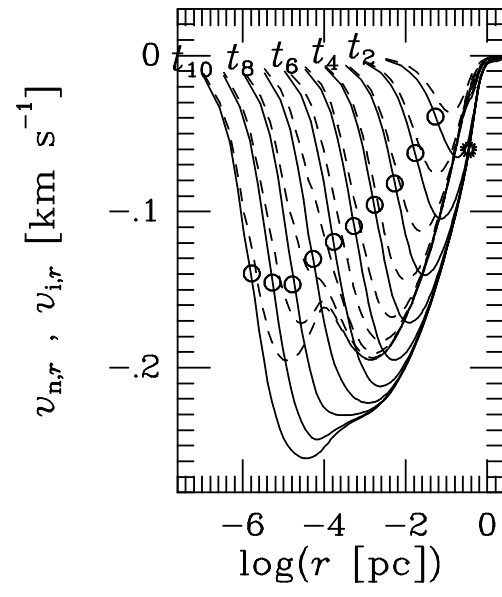
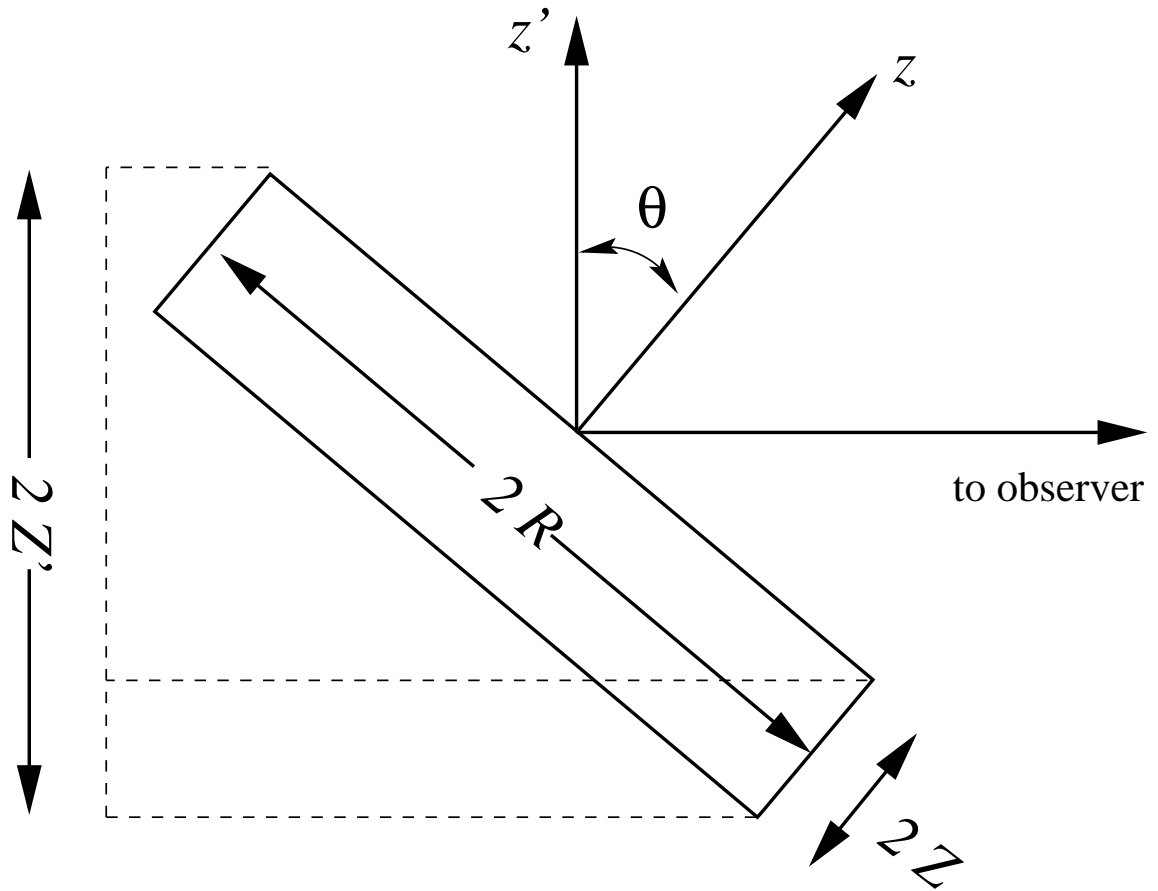


Fig. 2.—



$$\text{Apparent axial ratio} = q = (2Z'/2R) = \sin\theta + (Z/R) \cos\theta$$

Fig. 3.—

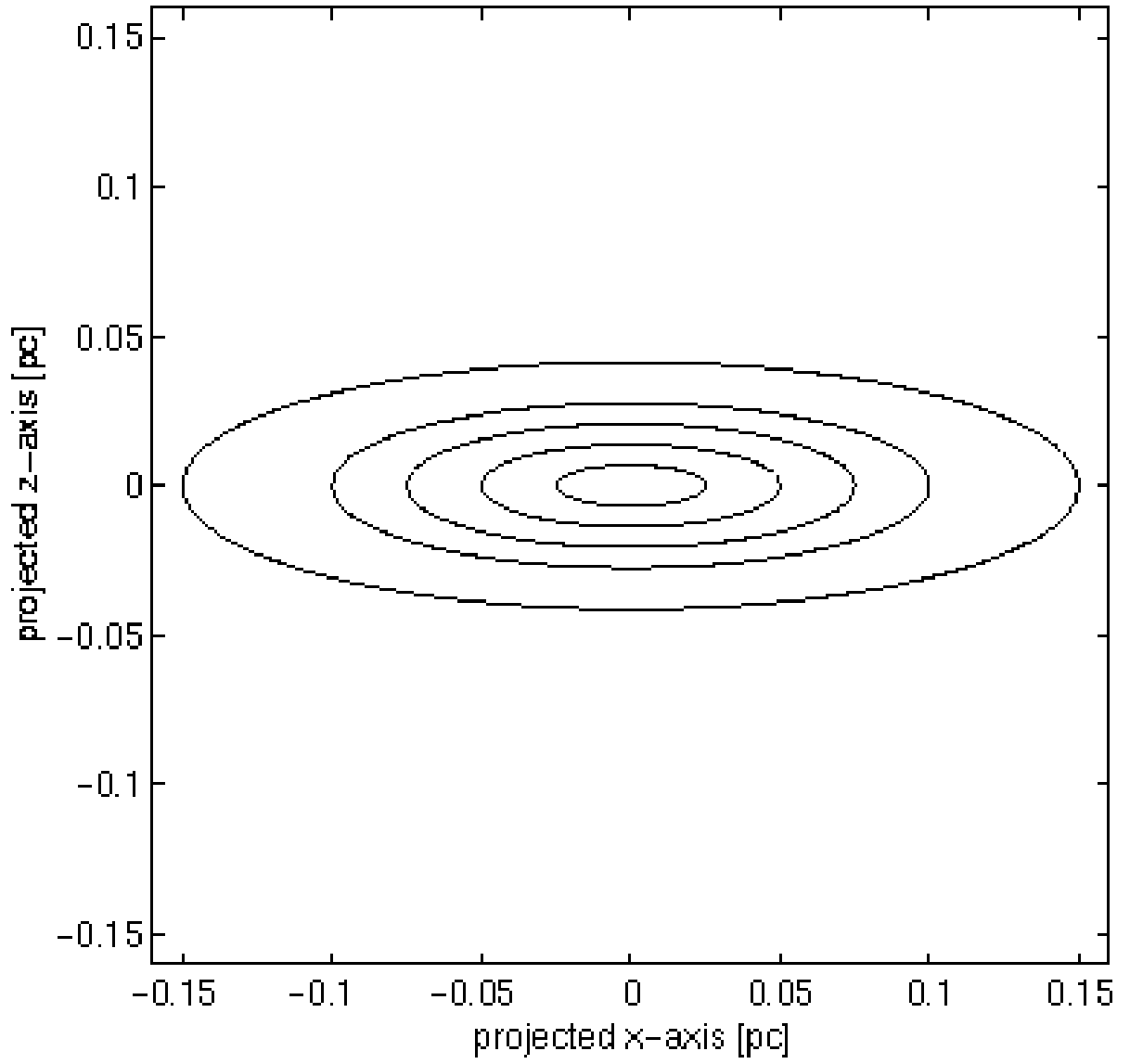


Fig. 4.—

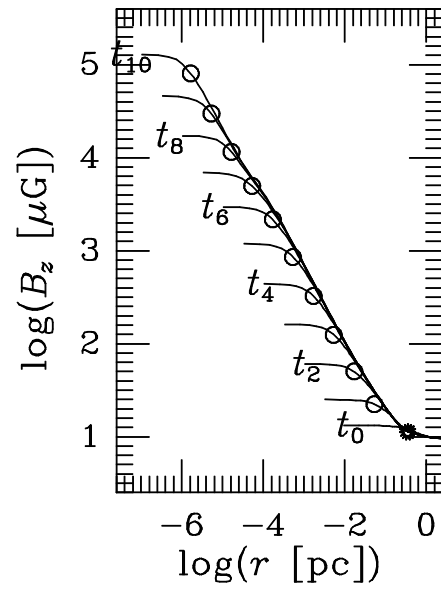
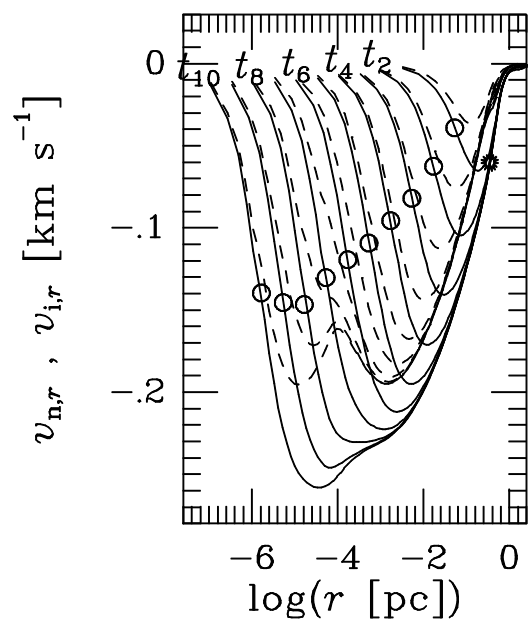
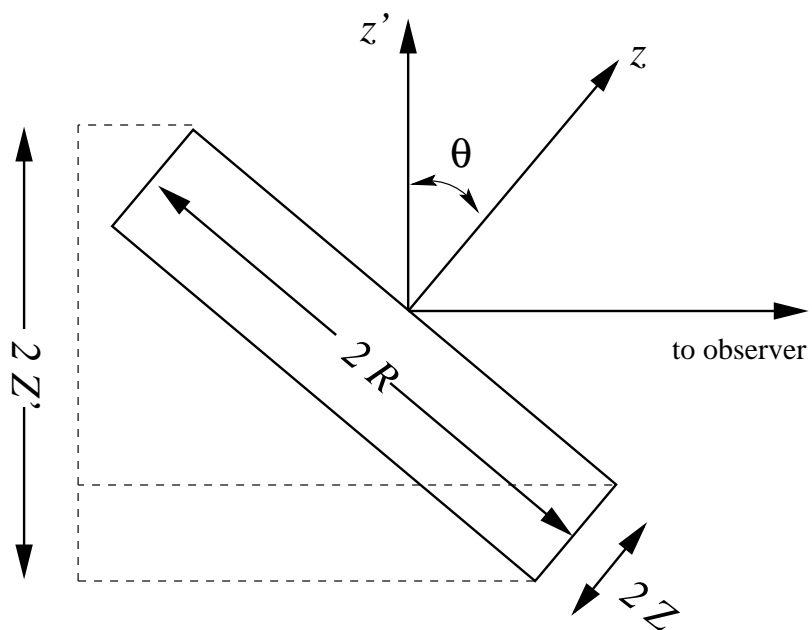


Fig. 5.—





Apparent axial ratio $= q = (2Z'/2R) = \sin\theta + (Z/R) \cos\theta$

